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(54) Gradient magnetic field coils

Magnetfeld-gradientenspule

Bobine à gradient de champ magnétique

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Description

[0001] The present invention relates to gradient magnetic field coils. It finds particular application in conjunction with gradient magnetic field coils for magnetic resonance imaging apparatus and will be described with particular ref rence thereto. However, it is to be appreciated that the present invention will also find application in conjunction with magnetic resonance spectroscopy systems and other applications which require gradient magnetic fields.

[0002] In a magnetic resonance imaging system, the gradient coils are commonly pulsed with current pulses having a short rise time and a high duty cycle. Pulsing the gradient coils produces magnetic field gradients across the imaging region, as well as magnetic field gradients which interact with external metallic structures such as cold shields in a superconducting magnet. This interaction generates eddy currents in the cold shields, which, in turn, generate eddy magnetic fields. The eddy fields have a deleterious effect on the temporal and spatial quality of the magnetic field in the examination region, hence in the resultant image quality.

[0003] One approach to circumventing the eddy current problem is to place a shielding coil between the gradient coil and the cold shields. The shielding coils are designed to substantially zero the magnetic field externally of themselves, preventing the formation of eddy currents. However, the shield coil inductively couples with the gradient coil, draws power, and reduces gradient coil efficiency. The required additional current through the gradient coil increases the already high demands on the driving circuit and the power handling capacity of the coils.

[0004] More specifically, gradient coils are typically a three-layered coil set that is formed on a cylindrical former. Coils for generating x, y, and z-gradients are insulated from each other and layered on the former. Commonly, the entire assembly is overwrapped and epoxy impregnated for greater structural strength to withstand the warping forces when the current carrying conductors interact with the primary magnetic field.

[0005] Various techniques have been employed to derive suitable conductor patterns for the gradient coils (Magn. Res. Med. 26 (1992) 191-206). Some gradient coil assemblies use a "distributed" coil design in which the conductors approximate a continuous current distribution function. Other coils begin with a discrete set of conductors which are closely bunched to one another. In both the distributed and bunched coils, the patterns are designed to meet specified electromagnetic design goals, particularly a linearity of the gradients with a minimal energy usage. To achieve these design goals, the radius of each coil is minimized. Minimizing the radius requires placing the coil layers close together in the radial direction. In some designs, the z-gradient coil, which is inherently the most efficient, is placed at the smallest radius. Confining the three coils in such close proximity creates numerous problems in design, fabrication, heat dissipation, and the like.

[0006] In order to simplify the system design of gradient shield coils, it is advantageous to drive primary and secondary coils in series. This is often referred to as self-shielding. In self-shielded gradient coils, there are generally two cylindrical coil sets. The larger diameter coil set substantially cancels the magnetic field exterior to itself but interacts with the smaller diameter coil to subtract from the gradient field in the examination region. A mechanical means connects the coil sets into a unitary structure while maintaining the coil sets in a spaced relationship. This type of self-shielded coil again reduces coil efficiency and increases power dissipation.

[0007] One of the problems with closely layered x, y, and z-coils is that the currents cause a significant amount of heat in a small confined area. The overwrap and epoxy impregnation resist the transfer of heat from the coil assembly. Although the z-coil is inherently more efficient than the x and y-coil, placing the z-coil as either the innermost or outermost layer fails to take advantage of this greater efficiency from a thermal standpoint. When the z-coil is the innermost coil, it is a heat source closer to the patient bore. Since it is generally layered into machined grooves in the former. Alternately, the innermost placement of the z-coil increases the radius of the already least efficient x and y-coils. When the z-coil is in the outermost layer but physically close the x and y-coils, the z-coil and the epoxy and overwrap add a substantial heat barrier for removing heat from the x and y-gradient coils.

[0008] Such a two coil set self-shielded gradient coil is illustrated in U.S. Patent No. 4,737,716 issued April 12, 1988 to Roemer, et al. The Roemer design approach was to expand the current density stream functions in a suitable Fourier-type series and derive a set of expansion coefficients which yield the desired field gradient linearity and screening/shielding behavior. The described Roemer design is iterative in nature. That is, a winding pattern is designed for the inner coil in a direct fashion. The outer coil is then designed to cancel the exterior magnetic field of the inner coil which, of course, disturbs the linearity of the magnetic field. This requires adjusting the inner coil design to maintain the linearity requirements, which requires adjusting the outer coil design, etc.

[0009] One problem with the Roemer method is that it does not consider the inductance or stored magnetic energy in the coil in a direct fashion. This permits the coil design to hold more than a minimal amount of energy, which is energy inefficient and forces one to iteratively search for a solution which is deemed acceptable. Linear, but very inefficient coils can be generated. Further, this technique does not take advantage of the inherent higher efficiency of z-gradient coils.

[0010] Another technique for designing self-shielded gradient coils which seeks to minimize inductance or energy storage is described in "Minimum Inductance Coils", R. Turner, J. Phys. E. Sci. Instrum. (19), 1986. Two cylinders

which are each assumed to have infinite length support continuous current density functions. Working in the spectral domain, the magnetic field is constrained at a finite number of points with the added constraint that the second cylinder is a superconducting boundary, i.e. the outer coil shields the surrounding structure from the magnetic field gradients. The stored magnetic energy is minimized with these constraints and a direct, analytic solution for the current distribution is obtained. The current distribution is then truncated to account for the finite length of the coils and discretized to produce a practical coil pattern.

[0011] One of the disadvantages of the Turner approach is that the coils are assumed to be of infinite length and then truncated. This creates aberrations in the resultant pattern and diminishes the effectiveness of the shielding, particularly adjacent the edges. Another disadvantage is that the field is defined only at a finite set of points. There is no direct control on how the magnetic field might behave between the points. Further, this technique does not take advantage of the greater efficiency found in z-gradient coils relative to x and y gradient coils.

[0012] A technique for designing bunched coils is set forth in UK Patent Application No. 2,180,943 of Mansfield, et al. and the corresponding US Patent No. 4,978,920. This published application provides sets of relationships which describe the induced current density in a superconducting cylinder due to the loops or arcs of segments of current flowing on a smaller diameter cylinder, i.e. the inner coil. However, this technique does not take advantage of the greater efficiency of the z-gradient coil.

[0013] Typically, x, y and z-gradient coils are mounted in concentric, bonded layers as illustrated in US Patent No. 4,733,189 to Punchard, et al. Active shield coils are mounted on three laminated layers of a concentric surrounding cylinder. One drawback of laminating the coils is that there is poor heat dissipation. The coils tend to heat, which can cause distortion of the physical structures and the resultant gradient or shielding magnetic fields.

[0014] Magn. Res. Med. 24 (1992) 29-41 also discloses x-gradient coils and y-gradient coils integrally bonded to a former, and also the provision of shield coils.

[0015] EP-A-0 152 588 discloses an arrangement in which x, y and z-gradient coils are not bonded to a former, but are connected by carrier elements to form a self-supporting coil basket which is attached to a cylindrical support body which surrounds an examination region via elastic support elements, to reduce the sound level in the cylindrical support body.

[0016] The present invention contemplates a new and improved self-shielded gradient coil and method for designing such self-shielded gradient coil which overcomes the above-referenced problems and others.

[0017] In accordance with one aspect of the present invention there is provided a self-shielded gradient coil assembly for a magnetic resonance apparatus comprising: an inner, tubular former which defines an examination region therein; an x-gradient coil and a y-gradient coil integrally bonded to the inner former; a z-gradient coil extending around the inner former and the x and y-gradient coils and arranged to produce a magnetic field gradient in a direction along the axis of the inner former and orthogonal to the directions of magnetic field gradients produced by the x and y-gradient coils; an outer tubular former disposed around the z-gradient coil; and x, y, and z shielding coils affixed to the outer former, characterised in that the z-gradient coil is spaced in a radial direction from the inner former and the x and y-gradient coils such that a generally annular cooling passage is defined therebetween.

[0018] The integral bonding of the x and y-gradient coils to the inner former provides structural support for the coils, while the generally annular cooling passage facilitates cooling of the coils.

[0019] According to a second aspect of the invention there is provided a magnetic resonance imaging apparatus including a self-shielded gradient coil assembly in accordance with the first aspect of the invention, comprising: an annular vacuum chamber which defines a cylindrical inner bore therein; an annular helium reservoir disposed within the vacuum chamber surrounding and displaced from the central bore thereof; a superconducting primary magnetic field coil disposed within the helium chamber for generating a substantially uniform magnetic field longitudinally through the central bore; and the self-shielded gradient coil assembly being disposed in the central bore for generating gradient magnetic fields across an examination region thereof and for shielding the vacuum chamber, the helium reservoir, and other components within the vacuum chamber from the generated gradient field magnetic fields such that eddy currents are not induced in the vacuum chamber or the contained associated structure, which eddy currents would tend to generate spurious magnetic fields within the bore; a radio frequency coil disposed within the vacuum chamber; a gradient control means for selectively causing electrical pulses to be applied to the gradient coil assembly for inducing magnetic gradient pulses across the examination region; a radio frequency transmitter for applying radio frequency pulses to the radio frequency coil for exciting and manipulating magnetic resonance of selected dipoles within the examination region; a receiver means for receiving and demodulating magnetic resonance signals emanating from the examination region; and a reconstruction means for reconstructing the demodulated magnetic resonance signals into an image representation.

[0020] According to a third aspect of the invention there is provided a method of designing a self-shielded gradient coil assembly according to the first aspect of the invention, in which an inner tubular former defines an examination region, an x-gradient coil and a y-gradient coil are integrally bonded to the former, a z-gradient coil extends around the x- and y-gradient coils, and x, y and z shielding gradient coils are affixed to an outer tubular former (80) disposed

around the z-gradient coil, the method comprising: selecting a radius for a primary gradient coil; selecting a radius for the z-gradient coil such that the z-gradient coil is spaced in a radial direction from the inner former and the x and y-gradient coils such that a generally annular cooling passage is defined therebetween; selecting a radius for a secondary, shielding gradient coil; designing a primary gradient coil pattern which achieves a preselected flux density and designing a corresponding secondary gradient coil; comparing the number of turns of the primary and secondary gradient coils; iteratively (i) adjusting a length of the primary gradient coil, (ii) redesigning for the primary gradient coil to achieve the preselected flux density, (iii) redesigning the corresponding secondary gradient coil, and (iv) determining the ratio of the numbers of turns of the primary and secondary gradient coils, until an integer ratio of the numbers of turns is achieved; truncating the secondary gradient coil to a length longer than the length of the primary gradient coil.

[0021] According to a fourth aspect of the invention there is provided a method of designing a self-shielding gradient coil assembly according to the third aspect of the invention, the method comprising: selecting an inner diameter, thickness, and maximum length of the self-shielding gradient coil; selecting a mean conductor radius for an x primary coil and a y primary coil; designating an outer diameter of the x and y primary coils and an associated supporting structure; selecting a mean z gradient coil radius which is at least 10 mm larger than said outer diameter to provide the generally annular cooling passage; setting a maximum outer diameter, thickness, and length of a secondary coil assembly; establishing mean radii of x, y, and z secondary coils; determining a current distribution of x and y coil patterns and adjusting the length of the primary coil assembly to optimize shielding while constraining derivatives of the magnetic field in order to control linearity; iteratively adjusting x and y coil patterns and adjusting the primary coil length until a minimum energy storage and maximum shielding and linearity are attained; adjusting the primary z gradient coil radius to optimize shielding while constraining derivatives of the magnetic field to control linearity.

[0022] One advantage of the present invention resides in the improved thermal cooling of the gradient coils, particularly the x and y-gradient coils.

[0023] Another advantage of the present invention resides in the improved shielding characteristics.

[0024] It is possible with the present invention to use shorter gradient coils with improved linearity.

[0025] Another advantage of the present invention resides in its energy efficiency.

[0026] A magnetic resonance imaging apparatus in accordance with the invention incorporating gradient coils in accordance with the invention designed by a method in accordance with the invention will now be described by way of example with reference to the accompanying drawings in which:-

Figure 1 is a vertical cross-sectional view of the magnetic resonance imaging apparatus through a vacuum envelope and various interior layers of a superconducting magnet;

Figure 2 is an enlarged, detailed view of a gradient coil assembly of Figure 1;

Figure 3 is a diagrammatic illustration of one of four symmetric quadrants of a primary x or y-gradient coil of the coil assembly of Figure 2, laid out flat;

Figure 4 is a top view of a primary z-gradient coil of Figure 2;

Figure 5 is a diagrammatic illustration of one of four symmetric quadrants of a preferred x or y-gradient shield coil of Figure 2, laid out flat;

Figure 6 is a diagrammatic illustration of a secondary z-gradient coil of Figure 2 with a secondary z-gradient coil cut longitudinally and opened out flat; and,

Figure 7 is a block diagram of a preferred method of determining primary and secondary or shielding x, y and z coil characteristics.

[0027] Referring to Figure 1, the apparatus includes a superconducting main magnet field coil assembly 10 which generates a substantially uniform magnetic field longitudinally through an examination region 12. A self-shielded gradient magnetic field coil assembly 14 selectively creates gradient magnetic fields across the examination region 12. A gradient magnetic field control means 16 controls a current pulse generator 18 to apply current pulses with selected characteristics to the gradient field coils to cause the desired magnetic field pulse to be generated.

[0028] A resonance excitation and manipulation means includes a radio frequency transmitter 20 for generating radio frequency pulses of the appropriate frequency and spectrum for inducing resonance of selected dipoles in the examination region 12. The radio frequency transmitter is connected with a radio frequency antenna 22 disposed surrounding the examination region and inside the gradient magnetic field coil assembly 14. The RF coil transmits radio frequency pulses into the region of interest and receives radio frequency resonance signals emanating therefrom. Alternately, a separate receiving coil may be provided. The received magnetic resonance signals are conveyed to a digital radio frequency receiver 24 for demodulation. The demodulated, digital radio frequency signals are reconstructed into a magnetic resonance image representation by an array processor or other image reconstruction means **26**. The reconstructed image representation is stored in an image memory **28**. The image representation may be displayed on a video monitor **30**, subject to further processing, stored on tape or disk, or the like.

[0029] The superconducting magnet assembly **10** includes an outer vacuum vessel **40** which defines an inner, cy-

lindrical room temperature bore **42** within which the gradient field coil assembly **14** is received. A series of superconducting, annular magnetic coils **44** are mounted on a dielectric former **46** and disposed within an annular helium reservoir **48**. A helium port **50** permits the helium reservoir **48** to be maintained filled with liquid helium as it evaporates to hold the temperature within the helium vessel about 4.2° K. Preferably, a helium recovery and recirculating system (not shown) is interconnected with the helium port **50**. The helium reservoir is surrounded by a first cold shield **52** which is cooled to about 200 K. or less. A second cold shield assembly **54**, which is chilled to about 60°-70° K. or less, is disposed between the inner cold shield assembly and the vacuum vessel **40**. In this way, a series of thermal gradations are maintained to minimize the evaporation of helium. A superconducting main magnetic field shield coil assembly **56** is mounted around the exterior of the superconducting magnet coils **44** and connected electrically in series therewith. The main field shield coil assembly **56** generates a magnetic field which opposes the fields generated by the main magnets **44** in the exterior of the cryostat, while producing a strong uniform magnetic field along the bore **42**.

[0030] With particular reference to FIGURE 2, the gradient coil assembly **14** includes an inner dielectric former **60** of radius **a**. Four x-gradient coils of the pattern illustrated in FIGURE 3 are laminated to the cylindrical surface of the inner former **60**. More specifically, for the x-gradient coil, the quadrant winding **62(x)** of FIGURE 3 is connected with a like quadrant winding along edge **64**, which like quadrant winding is a mirror image of the quadrant winding **62**. The pair of winding assemblies **62(x)** are laminated with the edge **64** at the longitudinal center of the former **60** and extending peripherally therearound. A like pair of coils are mounted opposite the longitudinal center and mirror image to the pair of coils **62(x)**. The y-gradient coils also include four coil segments **62(y)** which are of substantially the same construction. The y-gradient coils **62(y)** are mounted to the former **60** but 90° rotated about a central axis **66** of the former relative to the x-gradient coils. The x and y-gradient windings are electrically insulated from each other and preferably potted in an epoxy. The windings may be manufactured from a relatively thin conductive sheet, such as copper or aluminum. The sheet may be cut before lamination to the former by water jet cutting or the like, and then bonded to a thin insulating substrate. In this way, the radial thickness is minimized.

[0031] A primary z-gradient coil **70** of the construction shown in FIGURE 4 is constructed of a relatively stiff conductive material and connected with a series of mechanical positioning strips **72**. The mechanical positioning strips **72** are arranged periodically around the former **60** and connected thereto with insulating posts, or the like, to hold the primary z-gradient coil **70** in a spaced relationship to the x-gradient coils. In this manner, an air passage **74** is defined between the primary z-gradient coil and the primary x and y-gradient coils, with additional air passages defined through the z-gradient coil.

[0032] The former **60** is mounted by mechanical supporting means such as posts or vanes to a larger diameter shielding coil **80**. The shielding gradient coil **80** has a series of shielding coils laminated to a surface thereof. These shielding coils include four symmetric x-gradient shielding coil assemblies **82(x)** of the construction shown in FIGURE 5 mounted substantially in alignment with the windings **62** of the primary x-gradient coil. The shield coil further includes four y-gradient shielding coil assemblies **82(y)** also of the construction of FIGURE 5, but of the quadrants mounted 90° offset relative to central axis **66** from the x-gradient shielding coil assemblies and substantially in alignment with the four primary y-gradient quadrant windings **62**. The z-gradient coil construction **84** of the construction shown in FIGURE 6 is mounted in corresponding grooves in the former **80**. Because these shielding coils wrapped on former **80** have fewer turns and, therefore, much less resistance than the primary gradient coils wrapped on former **60**, heat dissipation is not as great a concern. Accordingly, the x, y, and z-gradient coils are all laminated to the former **80** for spatial efficiency.

[0033] With reference to FIGURE 7, first, the internal diameter, thickness, and length L_1 of the primary coil former are selected **100**. From the dimensions of the primary coil former **60**, a minimum radius **a** is set **102**. The thickness of the overwrap and impregnating resin is selected **104**, preferably as thin as possible while providing adequate dimensional stability and support. The finished outer diameter of the primary x and y-gradient coil assembly is determined **106**. A radius of the primary z coil is determined **108** by adding a minimum of 10 mm to the outer radius of the finished primary x and y coil assembly.

[0034] The outer diameter of the secondary coil assembly is selected **110** to be as large as possible, provided the secondary coil fits within the bore **42**. The thickness of the overwrap and impregnant which is necessary to provide the secondary coils with appropriate strength and stability is determined **112**. From the dimensions with the overwrap, the maximum available radius for the secondary x, y, and z coils is determined **114**. From the dimensions of the secondary x, y, and z coils, the dimensions of the secondary coil former **80** including its thickness, internal diameter, and length are determined **116**.

[0035] Although the diameter of the primary x and y coils and secondary x, y, and z coils are set in accordance with the diameter of the bore and the diameter of the minimum acceptable patient receiving region within the coils, the coil patterns are not yet optimized. The design of the x and y-gradient and secondary coils is determined **120** using Equations (1)-(23) below. It will be noted that once the radii of the coils are selected, the discrete Fourier transform coefficients j_ϕ^a can be identified and the primary current distribution J_ϕ^a can be determined from Equations (1) and (2) below. The primary winding pattern is constrained to an inner former length L_1 in a mathematical sense, while the secondary is

initially assumed to flow on an infinitely long cylinder. Next, the overall system of primary x and secondary x-gradient coil designs are optimized. Likewise, for the y-gradient, the magnetic energy W_m is determined pursuant to Equation (12) below. The linear combination F of the stored energy and various derivatives of the axial component of the magnetic flux density is determined from Equation (13). Due to the symmetry, many of the derivatives can be set to zero. The derivative term is expanded, preferably using a Fourier-Bessel integral for B_z as in Equation (10) and illustrated in Equation (14). With the derivative set to comply with the required characteristics, the function F is minimized with respect to the coefficients j_n^a which ultimately define the winding pattern of both the primary and secondary x and y-gradient coils.

[0036] After the characteristics of the primary and secondary x and y-gradient coils are determined, a turns ratio of the primary and secondary x and y-gradient coils is determined and compared **122** to determine whether there is an integer ratio of turns when driven in series. If the turns ratio is not an integer, then the length L_1 of the primary x and y-gradient coils is adjusted **124** and the x and y-gradient coils are designed **120** again. This process is repeated iteratively until an integer turns ratio is achieved. Once an integer turns ratio is achieved, the length L_2 of the secondary coils is truncated in order to fit the length of the secondary former selected in step **116** when the coils are discretized. This is typically the length of the bore **42**. The secondary coil length L_2 is longer, preferably at least 20% longer, than the selected length L_1 for the primary coils.

[0037] Once the primary and secondary x and y gradient coils design is fixed, the primary and secondary z-gradient coils are designed **130** using Equations (24)-(32) below. When designing the z-gradient coils, the adjustable variable is the radius of the primary z-gradient coil, rather than its length. As indicated in step **108**, the primary z-gradient coil can have a range of diameters, provided that it is sufficiently larger than the x and y primary coils to provide a cooling air gap in between. More specifically, because the z-gradient coils store much less energy than the x and y-gradient coils, it is, as a practical matter, not necessary to determine the minimum energy storage characteristics of the z-gradient coil. It should be appreciated, however, that this does not preclude using the same type of approach in Equations (1)-(23) to design the z-coil. The magnetic flux density B_z is determined pursuant to Equation (26). Its derivative in the z direction is determined pursuant to Equation (28). The various derivatives are set to zero or other values which obtain the selected z-gradient uniformity. In the preferred embodiment, the first derivative is the desired z-gradient. Higher order derivatives are considered undesirable and set to zero. The secondary z current j_φ^b is determined pursuant to Equation (29). Because the secondary z-gradient in the preferred embodiment is a bunched coil, the winding is discretized pursuant to Equation (30). The turns ratio of the primary and secondary z-coils is determined **132**. The radius of the primary z-coil is adjusted **134** and the z-gradient coil design step **130** repeated. This process is repeated iteratively until an integer turns ratio is achieved.

[0038] As stated more mathematically, a continuous vector surface current density function of radius ρ=a

$$J_\varphi^a(\varphi,z), J_z^a(\varphi,z)$$

is defined:

$$J_\varphi^a(\varphi,z) = \sum_{n=1}^{N} j_n^a \cos(k_n z)\cos\varphi \qquad (1),$$

$$J_z^a(\varphi,z) = \sum_{n=1}^{N} \frac{j_n^a}{k_n^a}\sin(k_n z)\sin\varphi \qquad (2),$$

where

$$k_n = 2n\pi/L_1 \qquad (3).$$

Their respective spatial Fourier transform coefficients

$$j_\varphi^a(m,k), j_z^a(m,k)$$

which are defined as:

$$j_\varphi^a(m,k) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\pi}^{\pi} J_\varphi^a(\varphi,z)\, e^{-im\varphi-ikz}\, d\varphi\, dz \qquad (4)$$

$$j_z^a(m,k) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\pi}^{\pi} J_z^a(\varphi,z)\, e^{-im\varphi-ikz}\, d\varphi\, dz \qquad (5)$$

and are given by:

$$j_\varphi^a(\pm 1,k) = \frac{L_1}{4}\sum_{n=1}^{N} j_n^a \Psi_{\varphi n}(k) \qquad (6)$$

$$j_z^a(\pm 1,k) = \pm\frac{L_1}{4}\sum_{n=1}^{N} \frac{j_n^a}{k_n a}\Psi_{zn}(k) \qquad (7),$$

where

$$\Psi_{\varphi n}(k) = \frac{\sin\{(k-k_n)L_1/2\}}{\{(k-k_n)L_1/2\}} + \frac{\sin\{(k+k_n)L_1/2\}}{\{(k+k_n)L_1/2\}} \qquad (8)$$

$$\Psi_{zn}(k) = -\frac{\sin\{(k-k_n)L_1/2\}}{\{(k-k_n)L_1/2\}} + \frac{\sin\{(k+k_n)L_1/2\}}{\{(k+k_n)L_1/2\}} \qquad (9).$$

With a superconducting cylindrical surface placed at radius b>a, the axial or z component of magnetic flux density B_z generated by the current density

$$J_\varphi^a, J_z^a$$

within the cylindrical surface ρ=a

$$B_z(\rho,\varphi,z) = -\frac{\mu_o a L}{4\pi}\cos(\varphi)\sum_{n=1}^{N} j_n^a \int_{-\infty}^{\infty} k\Psi_{\varphi n}(k)\cos(kz)\, I_1(k\rho)\, K'_1(ka)\, S_1(a,b,k)\, dk \qquad (10),$$

$$S_1(a,b,k) = 1-\frac{I'_1(ka)K'_1(kb)}{I'_1(kb)K'_1(ka)} \qquad (11).$$

The magnetic stored energy W_m is:

$$W_m = -\frac{\mu_o a^2 L^2}{16}\sum_{q=1}^{N}\sum_{n=1}^{N} j_q^a j_n^a \int_{-\infty}^{\infty} I'_1(ka)\,K'_1(ka)\,\Psi_{\varphi q}(k)\,\Psi_{\varphi n}(k)\,S_1(a,b,k)\,dk \qquad (12).$$

These equations apply for x-gradients and are simply rotated by 90° to give the corresponding equations for the y-gradient. Due to the purity of the azimuthal behavior of the field, ϕ may be arbitrarily set to 0.

[0039] As a next step, a functional F is formed involving the magnetic stored energy and various derivatives of the axial component of magnetic flux density:

$$F = W_m - \sum_{j=1,3,\ldots}\ \sum_{p=0,2,\ldots} \lambda_{jp}\left(\frac{\partial^p\partial^j B_z}{\partial z^p\,\partial\rho^j}\Big|_{\varphi=\rho=z=0} - G_{jp}^c\right) \qquad (13).$$

Due to symmetry, even-j and odd-p derivatives are naturally zero. Hence, these derivatives are not included in the above description of F. The constants G_{jp} in this expression represent desired or constrained values of corresponding derivatives of the z-component of the magnetic field, B_z and the λ's represent undetermined Lagrange multipliers. One can show that:

$$\frac{\partial^p\partial^j B_z}{\partial z^p\,\partial\rho^j}\Big|_{\varphi=\rho=z=0} = -\frac{\mu_o a L}{4\pi}\sum_{n=1}^{N} j_n^a(-1)^{p/2}\int_{-\infty}^{\infty} k^{p+j+1}\Psi_{\varphi n}(k)\,I_1^{(j)}(0)\,K'_1(ka)\,S_1(a,b,k)\,dk \qquad (14).$$

It is worth noting that, for example, if the p=0, j=5 derivative is constrained to be zero, then all combinations of p and j which add to order 5 are implicitly zero (i.e. [p,j]=[2,3],[4,1]). For this reason, we arbitrarily set p=0 and constrain only odd-j derivatives. Of course, the j=1 derivative is just the desired (non-zero) gradient strength.

[0040] With this background, the final steps of the coil design method are described. The functional F is extremized with respect to the unknown coefficients j_n^a. A matrix equation results and is given by:

$$\sum_{q=1}^{N} j_q^a\left\{\int_0^{\infty} I'_1(ka)\,K'_1(ka)\,S_1(a,b,k,)\,\Psi_{\varphi q}(k)\,\Psi_{\varphi n}(k)\,dk\right\} = \sum_j \lambda_j\left\{\frac{2}{\pi a L}\int_0^{\infty} k^{j+1}\Psi_{\varphi n}(k)\,I_1^{(j)}(0)\,K'_1(ka)\,S_1(a,b,k)\,dk\right\} \qquad (15)$$

for n=1,2,...,N.

[0041] This is written in the compact form:

$$\sum_q j_q^a C_{nq} = \sum_j \lambda_j D_{jn} \qquad (16)$$

for n=1, 2, ..., N or

$$J^{a} = \Lambda D C^{-1} \qquad (17).$$

Enforcing the constraints discussed above on the various derivatives gives an additional relation which can be written as:

$$G_j^c = -\frac{\mu_o a^2 L^2}{4} \sum_{n=1}^{N} j_n^a D_{jn} \qquad (18)$$

for $j=1, 3, ..., J_{max}$ or

$$G^c = -\frac{\mu_o a^2 L^2}{4} J^a D^T \qquad (19).$$

The relations of Equations (17) and (19) are combined to give a solution for Λ in the form:

$$\Lambda = -\frac{4}{\mu_o a^2 L_1^2} G^c (D C^{-1} D^T)^{-1} \qquad (20).$$

The shield current flowing on the cylinder of radius b is expressed as:

$$j_\varphi^b(\pm 1, k) = -j_\varphi^a(\pm 1, k) \frac{a I'_1(ka)}{b I'_1(kb)} \qquad (21)$$

$$j_z^b(\pm 1, k) = \mp \frac{1}{kb} j_\varphi^b(\pm 1, k) \qquad (22)$$

Once the solutions for the continuous current density functions are in hand, we select a discrete conductor arrangement which substantially approximates these through discretization of stream functions $S^{a,b}$, whereby:

$$\vec{J}^{a,b} = \nabla \times \vec{S}^{a,b} \qquad (23).$$

In a preferred embodiment, the solution $J^{a,b}$ is varied by adjusting the length L_1 of the primary coil until an integer number of contours of constant $S^{a,b}$ are obtained. This procedure ensures good shielding characteristics. In practice, the shield current extends farther than the primary current distribution and is apodized or truncated to produce a practical coil length.

[0042] In a preferred embodiment there are N=4 terms in the expansion for the currents and the j=3 and j=5 derivatives are set to zero. The j=1 derivative is constrained to the desired gradient strength.

[0043] The primary or inner z-gradient coil is preferably bunched and is modeled as a series of pulse surface currents flowing on a circular cylinder of radius a:

$$J_\varphi^a(z) = \sum_{q=1}^{Q} K_q \left\{ \begin{aligned} &\left(U\left(z - z_q + \frac{W_q}{2}\right) - U\left(z - z_q - \frac{W_q}{2}\right) \right) \\ &-\left(U\left(z + z_q + \frac{W_q}{2}\right) - U\left(z + z_q - \frac{W_q}{2}\right) \right) \end{aligned} \right\} \qquad (24),$$

where K_q is the linear current density, W_q the width and +/- z_q the axial positions of the q-th azimuthal sheet current.

U( ) is a usual unit Heviside step function. Notice that the current sheets come as antisymmetric pairs. The spatial Fourier transform coefficients $j_\phi{}^a$ of this current distribution are given by:

$$j_\phi^a(k) = -i2\sum_{q=1}^{Q} (K_q w_q)(kz_q)\,\mathrm{Sinc}(kz_q)\,\mathrm{Sinc}\left(\frac{kq_q}{2}\right) \qquad (25).$$

It is noted that $K_q w_q$ is just the total q-th current, I_q. For a superconducting cylindrical surface at radius b>a, the expression for the axial or z-component of magnetic flux $B_z(\rho,z)$ density is:

$$B_z(\rho,z) = \frac{-\mu_o a}{2\pi}\int_{-\infty}^{\infty} k e^{ikz} j_\phi^a(k)\, S_0(a,b,k)\, K'_0(ka)\, I_0(k\rho)\, dk \qquad (26),$$

where

$$S_0(a,b,k) = 1 - \frac{I'_0(ka)K'_0(kb)}{I'_0(kb)K'_0(ka)} \qquad (27).$$

From the Equation (26) expression for B_z, the j-th axial derivative of the field at the origin is obtained as follows (only odd-j derivatives are non-zero due to symmetry):

$$\frac{\partial^j B_z}{\partial z^j}\Big|_{\rho=z=0} = \frac{-\mu_o a}{\pi} i^j \int_0^{\infty} k^{j+1} j_\phi^a(k)\, S_0(a,b,k)\, K'_0(ka)\, dk \qquad (28).$$

The j=1 derivative is just the desired gradient and the j>1 derivatives represent contaminants. In a preferred embodiment, there are two pairs of antisymmetric current sheets such that $I_2/I_1=W_2/W_1 = 7$, $K_2=K_1$ and Z_2 and Z_1 are chosen to give substantially zero j=3 and j=5 derivatives. The shielding current on the cylinder at radius b is given by:

$$j_\varphi{}^b(k) = -j_\varphi{}^a(k)\frac{aI'_0(ka)}{bI'_0(kb)} \qquad (29)$$

which is inverse Fourier transformed to give the current distribution $J_\phi{}^b$ in the spatial domain, i.e. the physical coil winding pattern.

[0044] In a preferred embodiment, the shield current distribution is discretized using conductors of constant cross-section and is driven in series with the primary coil. The positions, for z>0 are determined using a center-of-mass definition as follows:

$$z_m = \frac{1}{-I_{peak}}\int_{z_{m-}}^{z_{m+}} zJ_\phi^b(z)\,dz \qquad (30),$$

where

$$\int_{z_{m-}}^{z_{m+}} J_\phi^b(z)\,dz = -I_{peak} \qquad (31)$$

m=1,2,...,M.

[0045] The value of M is set to the nearest integer of the quantity:

$$\{-\int_0^{z_o} J_\varphi^b(z)\,dz\}/I_{peak} \qquad (32).$$

The upper bound is set large enough that the value of J(z) is substantially zero beyond this point. In a preferred embodiment, and for the purpose of giving optimal shielding characteristics, the radius a (or b, or both) is adjusted so that the quantity of Equation (32) is an integer value.

[0046] In an alternate embodiment, the z primary current is not assumed to be a series of pulse sheet currents, but instead is allowed to be a Fourier series-type function similar to the Y/X case. The same constrained energy minimization procedure is then followed to design the z-gradient. In this alternate embodiment, the z primary current is distributed and similar relations for its discretization to that described above are developed. Again, the radii a and b are preferably adjusted to give an integer number of turns for both the primary and shield coils for optimal shielding.

Claims

1. A self-shielded gradient coil assembly (14) for a magnetic resonance apparatus comprising: an inner, tubular former (60) which defines an examination region therein; an x-gradient coil (62(x)) and a y-gradient coil (62(y)) integrally bonded to the inner former; a z-gradient coil (70) extending around the inner former and the x and y-gradient coils and arranged to produce a magnetic field gradient in a direction along the axis of the inner former and orthogonal to the directions of magnetic field gradients produced by the x and y-gradient coils; an outer tubular former (80) disposed around the z-gradient coil; and x, y, and z shielding coils (82(x), 82(y), 84) affixed to the outer former, characterised in that the z-gradient coil (70) is spaced in a radial direction from the inner former and the x and y-gradient coils such that a generally annular cooling passage (74) is defined therebetween.

2. A self-shielded coil assembly according to Claim 1, wherein the coils have bunched winding patterns.

3. A self-shielded coil assembly according to Claim 1 or Claim 2, wherein the inner former (60) has a length and a diameter selected such that the x and y-gradient coils (62(x), 62(y)) achieve preselected x and y-gradient fields with an integer number of turns.

4. A self-shielded gradient coil assembly according to Claim 3, wherein the diameter of the outer former (80) is selected such that the x and y shielding coils (82(x), 82(y)) shield the x and y-gradient fields from the x and y-gradient coils with an integer number of turns, when driven with the same current amplitude as the x and y-gradient coils.

5. A self-shielded coil assembly according to any one of Claims 1 to 4, wherein at least the z-gradient coil (70) and the z shielding coil (84) have radii such that the ratio of the number of turns of the z-gradient coil and the z-gradient shield coil is an integer.

6. A magnetic resonance imaging apparatus including a self-shielded gradient coil assembly according to any one of Claims 1 to 5, comprising: an annular vacuum chamber (40) which defines a cylindrical inner bore (42) therein; an annular helium reservoir (48) disposed within the vacuum chamber surrounding and displaced from the central bore thereof; a superconducting primary magnetic field coil (44) disposed within the helium chamber for generating a substantially uniform magnetic field longitudinally through the central bore; and the self-shielded gradient coil assembly (14) being disposed in the central bore for generating gradient magnetic fields across an examination region thereof and for shielding the vacuum chamber, the helium reservoir, and other components within the vacuum chamber from the generated gradient field magnetic fields such that eddy currents are not induced in the vacuum chamber or the contained associated structure, which eddy currents would tend to generate spurious magnetic fields within the bore; a radio frequency coil (22) disposed within the vacuum chamber; a gradient control means (16) for selectively causing electrical pulses to be applied to the gradient coil assembly for inducing magnetic gradient pulses across the examination region; a radio frequency transmitter (20) for applying radio frequency pulses to the radio frequency coil for exciting and manipulating magnetic resonance of selected dipoles within the examination region; a receiver means (24) for receiving and demodulating magnetic resonance signals emanating from the examination region; and a reconstruction means (26) for reconstructing the demodulated magnetic res-

onance signals into an image representation.

7. A method of designing a self-shielded gradient coil assembly in which an inner tubular former (60) defines an examination region, an x-gradient coil (62(x)) and a y-gradient coil (62(y)) are integrally bonded to the former, a z-gradient coil (70) extends around the x- and y-gradient coils, and x, y and z shielding gradient coils (82(x), 82 (y), 84) are affixed to an outer tubular former (80) disposed around the z-gradient coil, the method comprising: selecting a radius for a primary gradient coil (62(x), 62(y), 70); selecting a radius for the z-gradient coil such that the z-gradient coil is spaced in a radial direction from the inner former and the x and y-gradient coils such that a generally annular cooling passage (74) is defined therebetween; selecting a radius for a secondary, shielding gradient coil (82(x), 82(y), 84); designing a primary gradient coil pattern which achieves a preselected flux density and designing a corresponding secondary gradient coil; comparing the number of turns of the primary and secondary gradient coils; iteratively (i) adjusting a length of the primary gradient coil, (ii) redesigning for the primary gradient coil to achieve the preselected flux density, (iii) redesigning the corresponding secondary gradient coil, and (iv) determining the ratio of the numbers of turns of the primary and secondary gradient coils, until an integer ratio of the numbers of turns is achieved; truncating the secondary gradient coil to a length longer than the length of the primary gradient coil.

8. A method of designing a self-shielding gradient coil assembly according to Claim 7, the method comprising: selecting an inner diameter, thickness, and a maximum length of the self-shielding gradient coil; selecting a mean radius for an x primary coil (62(x)) and a y primary coil (62(y)); designating an outer diameter of the x and y primary coils and an associated supporting structure; selecting a mean z gradient coil radius which is at least 10 mm larger than said outer diameter to provide said generally annular cooling passage (74); setting a maximum outer diameter, thickness, and length of a secondary coil assembly; establishing mean radii of x, y, and z secondary coils (82(x), 82(y), 84); determining a current distribution of x and y coil patterns and adjusting the length of the primary coil assembly to optimize shielding while constraining derivatives of the magnetic field in order to control linearity; iteratively adjusting x and y coil patterns and adjusting the primary coil length until a minimum energy storage and maximum shielding and linearity are attained; adjusting the primary z gradient coil radius to optimize shielding while constraining derivatives of the magnetic field to control linearity.

Patentansprüche

1. Eine selbstabschirmende Gradientenspulenanordnung (14) für einen Magnetresonanztomographen, die aufweist: einen inneren röhrenförmigen Spulenkörper (60), der einen Untersuchungsbereich in dieser bestimmt; eine x-Gradientenspule (62(x)) und eine y-Gradientenspule (62(y)), die integral an den inneren Spulenkörper angefügt sind; eine z-Gradientenspule (70), die sich um den inneren Spulenkörper und die x- und y-Gradientenspulen herum erstreckt und so vorgesehen ist, daß sie einen Magnetfeldgradienten in einer Richtung längs der Achse des inneren Spulenkörpers und orthogonal zu den Richtungen der von den x- und y-Gradientenspulen erzeugten Magnetfeldgradienten erzeugt; einen äußeren röhrenförmigen Spulenkörper (80), der um die z-Gradientenspule herum angeordnet ist; und x-, y- und z-Abschirmspulen (82(x), 82(y), 84), die an dem äußeren Spulenkörper befestigt sind,
dadurch gekennzeichnet,
daß die z-Gradientenspule (70) in radialer Richtung von dem inneren Spulenkörper und den x- und y-Gradientenspulen beabstandet ist, so daß dazwischen eine im allgemeinen ringförmige Kühlungsdurchführung (74) definiert wird.

2. Eine selbstabschirmende Gradientenspulenanordnung nach Anspruch 1, wobei die Spulen gebündelte Windungsmuster aufweisen.

3. Eine selbstabschirmende Gradientenspulenanordnung nach Anspruch 1 oder 2, wobei die Länge und der Durchmesser des inneren Spulenkörpers (60) so gewählt wird, daß die x- und y-Gradientenspulen (62(x), 62(y)) mit einer ganzzahligen Anzahl von Windungen festgesetzte x- und y-Gradientenfelder erreichen.

4. Eine selbstabschirmende Gradientenspulenanordnung nach Anspruch 3, wobei der Durchmesser des äußeren Spulenkörpers (80) so gewählt wird, daß die x- und y-Abschirmspulen (82(x), 82(y)) die x- und y-Gradientenfelder der x- und y-Gradientenspulen mit einer ganzzahligen Anzahl von Windungen abschirmen, wenn sie mit derselben Stromamplitude wie die x- und y-Gradientenspulen betrieben werden.

5. Eine selbstabschirmende Gradientenspulenanordnung nach einem der Ansprüche 1 bis 4, wobei mindestens die

z-Gradientenspule (70) und die z-Abschirmspule (84) solche Radien aufweisen, daß das Verhältnis der Anzahl der Windungen der z-Gradientenspule und der z-Abschirmgradientenspule ganzzahlig ist.

6. Ein Gerät zur Bilderzeugung durch magnetische Resonanz, das eine selbstabschirmende Gradientenspulenanordnung nach einem der Ansprüche 1 bis 5 beinhaltet, welches aufweist: eine ringförmige Vakuumkammer (40), welche eine innere zylindrische Öffnung (42) in sich definiert; einen ringförmigen Heliumbehälter (48), der innerhalb der Vakuumkammer angeordnet ist, wobei er deren mittige Öffnung umgibt und von dieser beabstandet ist; eine supraleitende Primärmagnetfeldspule (44), die innerhalb der Heliumkammer angeordnet ist, um ein im wesentlichen homogenes Magnetfeld in Längsrichtung durch die mittige Öffnung zu erzeugen; und wobei die selbstabschirmende Gradientenspulenanordnung (14) in der mittigen Öffnung angeordnet ist, um Gradientenmagnetfelder in einem Untersuchungsbereich innerhalb dieser zu erzeugen und um die Vakuumkammer, den Heliumbehälter und andere Komponenten innerhalb der Vakuumkammer von den erzeugten Gradientenfeldmagnetfeldern abzuschirmen, so daß in der Vakuumkammer oder den zugehörigen enthaltenen Vorrichtungen keine Wirbelströme induziert werden, welche Störmagnetfelder innerhalb der Öffnung erzeugen würden; eine Hochfrequenzspule (22), die innerhalb der Vakuumkammer angeordnet ist; eine Gradientensteuereinrichtung (16) zur selektiven Verursachung von auf die Gradientenspulenanordnung anzulegender Impulse, um Magnetgradientenimpulse in dem Untersuchungsbereich zu induzieren; einen Hochfrequenzsender (20) zum Einspeisen von Hochfrequenzimpulsen in die Hochfrequenzspule, um magnetische Resonanz ausgewählter Dipole innerhalb des Untersuchungsbereiches anzuregen und zu manipulieren; eine Empfangseinrichtung (24) zum Empfang und zur Demodulierung von Magnetresonanzsignalen, die aus dem Untersuchungsbereich ausstrahlen; und eine Rekonstruktionseinrichtung (26) zur Rekonstruktion der demodulierten Magnetresonanzsignale in eine Bilddarstellung.

7. Ein Verfahren zum Entwurf einer selbstabschirmenden Gradientenspulenanordnung, bei welcher ein innerer röhrenförmiger Spulenkörper (60) einen Untersuchungsbereich definiert, eine x-Gradientenspule (62(x)) und eine y-Gradientenspule (62(y)) integral an letzteren angefügt sind; eine z-Gradientenspule (70) sich um die x- und y-Gradientenspulen herum erstreckt und in einer radialen Richtung von dem inneren Spulenkörper und den x- und y-Gradientenspulen beabstandet ist, so daß dazwischen eine im allgemeinen ringförmige Kühlungsdurchführung (74) definiert wird, und wobei x-, y- und z-Abschirmgradientenspulen (82(x), 82(y), 84), an einem äußeren röhrenförmigen Spulenkörper (80) befestigt sind, der um die z-Gradientenspule angeordnet ist, wobei das Verfahren beinhaltet:
Auswahl eines Radius für eine Primärgradientenspule (62(x), 62(y), 70); Auswahl eines Radius für eine z-Gradientenspule, so daß die z-Gradientenspule in einer radialen Richtung von dem inneren Spulenkörper und den x- und y- Gradientenspulen beabstandet ist, so daß dazwischen eine im allgemeinen ringförmige Kühlungsdurchführung (74) definiert wird; Auswahl eines Radius für eine Sekundärabschirmgradientenspule (82(x), 82(y), 84); Entwurf eines Musters für die Primärgradientenspulen, welches eine festgesetzte Flußdichte erreicht und Entwurf einer entsprechenden Sekundärgradientenspule; Vergleich der Anzahl der Windungen der Primär- und Sekundärgradientenspulen; iterative (i) Anpassung einer Länge der Primärgradientenspule, (ii) Neuentwurf der Primärgradientenspule, um die festgesetzte Flußdichte zu erreichen, (iii) Neuentwurf der entsprechenden Sekundärgradientenspule, und (iv) Bestimmung des Verhältnisses der Anzahl der Windungen der Primär- und der Sekundärgradientenspulen, bis ein ganzzahliges Verhältnis der Windungsanzahl erreicht ist; Kürzung der Sekundärgradientenspule auf eine Länge, die länger ist als die Länge der Primärgradientenspule.

8. Ein Verfahren zum Entwurf einer selbstabschirmenden Gradientenspulenanordnung nach Anspruch 7, wobei das Verfahren beinhaltet: Auswahl eines Innendurchmessers, einer Dicke und einer maximalen Länge der selbstabschirmenden Gradientenspule; Auswahl eines Hauptradius für eine x-Primärspule (62(x)) und eine y-Primärspule (62(y)); Bestimmung eines Außendurchmessers der x- und y-Primärspulen und einer zugehörigen Halterungsvorrichtung; Auswahl eines Hauptradius der z-Gradientenspule, der mindestens 10mm größer ist als der Außendurchmesser, um die im allgemeinen ringförmige Kühlungsdurchführung (74) bereitzustellen; Festsetzen eines maximalen Außendurchmessers, einer maximalen Dicke und Länge einer Sekundärspulenanordnung; Festsetzen der Hauptradien der x-, y- und z-Sekundärspulen (82(x), 82(y), 84); Bestimmung einer Stromverteilung der Muster der x- und y-Spulen und Anpassung der Länge der Primärspulenanordnung, um die Abschirmung zu optimieren, wobei Ableitungen des magnetischen Feldes eingegrenzt werden, um die Linearität zu kontrollieren; iterative Anpassung der Muster der x- und y-Spule und Anpassung der Länge der Primärspule, bis eine minimale Energiespeicherung und maximale Abschirmung und Linearität erreicht sind; Anpassung des Radius der z-Primärgradientenspule, um die Abschirmung zu optimieren, wobei Ableitungen des magnetischen Feldes eingegrenzt werden, um die Linearität zu kontrollieren.

Revendications

1. Ensemble (14) de bobines de gradient à protection intégrée, destiné à un appareil de résonance magnétique, comprenant un organe formateur tubulaire interne (60) qui délimite une région d'examen à l'intérieur, une bobine de gradient x (62(x)) et une bobine de gradient y (62(y)) liées sous forme solidaire à l'organe formateur interne, une bobine de gradient z (70) qui s'étend autour de l'organe formateur interne et des bobines de gradient x et y et est disposée afin qu'elle produise un gradient de champ magnétique dans une direction qui se trouve le long de l'axe de l'organe formateur interne et qui est perpendiculaire aux directions des gradients de champ magnétique produits par les bobines de gradient x et y, un organe formateur tubulaire externe (80) disposé autour de la bobine de gradient z, et des bobines de protection x, y, z (82(x), 82(y), 84) fixées à l'organe formateur externe, caractérisé en ce que la bobine de gradient z (70) est espacée en direction radiale par rapport à l'organe formateur interne et aux bobines de gradient x et y afin qu'un passage (74) de refroidissement de forme générale annulaire soit délimité entre eux.

2. Ensemble de bobines à protection intégrée selon la revendication 1, dans lequel les bobines ont des diagrammes d'enroulement regroupés.

3. Ensemble de bobines à protection intégrée selon la revendication 1 ou 2, dans lequel l'organe formateur interne (60) a une longueur et un diamètre choisis de manière que les bobines de gradient x et y (62(x), 62(y)) donnent des champs prédéterminés de gradient x et y avec un nombre entier de spires.

4. Ensemble de bobines de gradient à protection intégrée selon la revendication 3, dans lequel le diamètre de l'organe formateur externe (80) est sélectionné de manière que les bobines de protection x et y (82(x), 82(y)) protègent les champs de gradient x et y des bobines de gradient x et y avec un nombre entier de spires, lors d'un pilotage avec la même intensité du courant que les bobines de gradient x et y.

5. Ensemble de bobines à protection intégrée selon l'une quelconque des revendications 1 à 4, dans lequel la bobine de gradient z (70) et la bobine de protection z (84) au moins ont des rayons tels que le rapport du nombre de spires de la bobine de gradient z et de la bobine de protection de gradient z est un nombre entier.

6. Appareil d'imagerie par résonance magnétique, comprenant un ensemble de bobines de gradient à protection intégrée selon l'une quelconque des revendications 1 à 5, comprenant une chambre annulaire (40) de vide qui délimite un trou interne cylindrique (42), un réservoir annulaire (48) d'hélium placé dans la chambre de vide autour du trou central et décalé par rapport à celui-ci, une bobine supraconductrice (44) de champ magnétique primaire disposée dans la chambre d'hélium et destinée à créer un champ magnétique pratiquement uniforme longitudinalement dans le trou central, et l'ensemble (14) de bobines de gradient à protection intégrée est disposé dans le trou central afin qu'il crée des champs magnétiques de gradient dans une région d'examen et qu'il protège la chambre de vide, le réservoir d'hélium et les autres éléments constituants placés dans la chambre de vide contre les champs magnétiques dus aux champs de gradient créés si bien que des courants de Foucault ne sont pas induits dans la chambre de vide ni dans la structure associée qu'elle contient, les courants de Foucault pouvant avoir tendance à créer des champs magnétiques parasites dans le trou, une bobine (22) à hautes fréquences disposée à l'intérieur de la chambre de vide, un dispositif (16) de réglage de gradient destiné à provoquer l'application sélective d'impulsions électriques à l'ensemble de bobines de gradient pour l'induction d'impulsions de gradient magnétique dans la région d'examen, un émetteur (20) de hautes fréquences destiné à appliquer des impulsions à hautes fréquences à la bobine de hautes fréquences pour l'excitation et la manipulation de la résonance magnétique de dipôles choisis dans la région d'examen, un dispositif récepteur (24) destiné à recevoir et démoduler les signaux de résonance magnétique provenant de la région d'examen, et un dispositif (26) de reconstruction des signaux démodulés de résonance magnétique sous forme d'une représentation d'image.

7. Procédé de réalisation d'un ensemble de bobines de gradient à protection intégrée, dans lequel un organe tubulaire formateur interne (60) délimite une région d'examen, une bobine de gradient x (62(x)) et une bobine de gradient y (62(y)) sont liées à l'organe formateur dont elles sont solidaires, une bobine de gradient z (70) s'étend autour des bobines de gradient x et z, et des bobines protectrices de gradient x, y et z (82(x), 82(y), 84) sont fixées à un organe tubulaire formateur externe (80) disposé autour de la bobine de gradient z, le procédé comprenant la sélection d'un rayon de bobine de gradient primaire (62(x), 62(y), 70) et la sélection d'un rayon pour la bobine de gradient de manière que la bobine de gradient z soit placée à distance en direction radiale de l'organe formateur interne et des bobines de gradient x et y afin qu'un passage de refroidissement (74) de forme générale annulaire soit délimité entre eux, la sélection d'un rayon pour une bobine de gradient secondaire de protection (82(x), 82(y),

84), la réalisation d'un diagramme de bobine de gradient primaire qui donne une densité prédéterminée de flux et la détermination d'une bobine de gradient secondaire correspondante, la comparaison du nombre de spires des bobines de gradient primaire et secondaire, puis, dans des opérations réalisées par itération, (i) l'ajustement de la longueur de la bobine de gradient primaire, (ii) la modification de la bobine de gradient primaire pour l'obtention de la densité prédéterminée de flux, (iii) la modification de la bobine correspondante de gradient secondaire, et (iv) la détermination du rapport au nombre de spires des bobines de gradient primaire et secondaire, jusqu'à ce qu'un rapport entier de nombre de spires soit obtenu, et la troncature de la bobine de gradient secondaire à une longueur supérieure à la longueur de la bobine de gradient primaire.

8. Procédé de réalisation d'un ensemble de bobines de gradient à protection intégrée selon la revendication 7, le procédé comprenant la sélection du diamètre interne, de l'épaisseur et de la longueur maximales de la bobine de gradient à protection intégrée, la sélection d'un rayon moyen d'une bobine primaire x (62(x)) et d'une bobine primaire y (62(y)), la désignation d'un diamètre externe des bobines primaires x et y et d'une structure associée de support, la sélection d'un rayon moyen de bobine de gradient z qui est supérieur d'au moins 10 mm au diamètre externe afin que le passage de refroidissement (74) de forme générale annulaire soit formé, le réglage du diamètre externe maximal, de l'épaisseur et de la longueur d'un ensemble de bobines secondaires, l'établissement des rayons moyens des bobines secondaires x, y et z (82 (x), 82 (y), 84), la détermination d'une distribution de courant des diagrammes des bobines x et y et l'ajustement de la longueur de l'ensemble de bobines primaires pour l'optimisation de la protection avec limitation des dérivées du champ magnétique afin que la linéarité soit maîtrisée, dans des opérations effectuées par itération, l'ajustement des diagrammes des bobines x et y et l'ajustement de la longueur de la bobine primaire jusqu'à l'obtention d'une accumulation minimale d'énergie et d'une protection et d'une linéarité maximales, et l'ajustement du rayon de la bobine de gradient z primaire pour l'optimisation de la protection avec réduction des dérivées du champ magnétique afin que la linéarité soit maîtrisée.

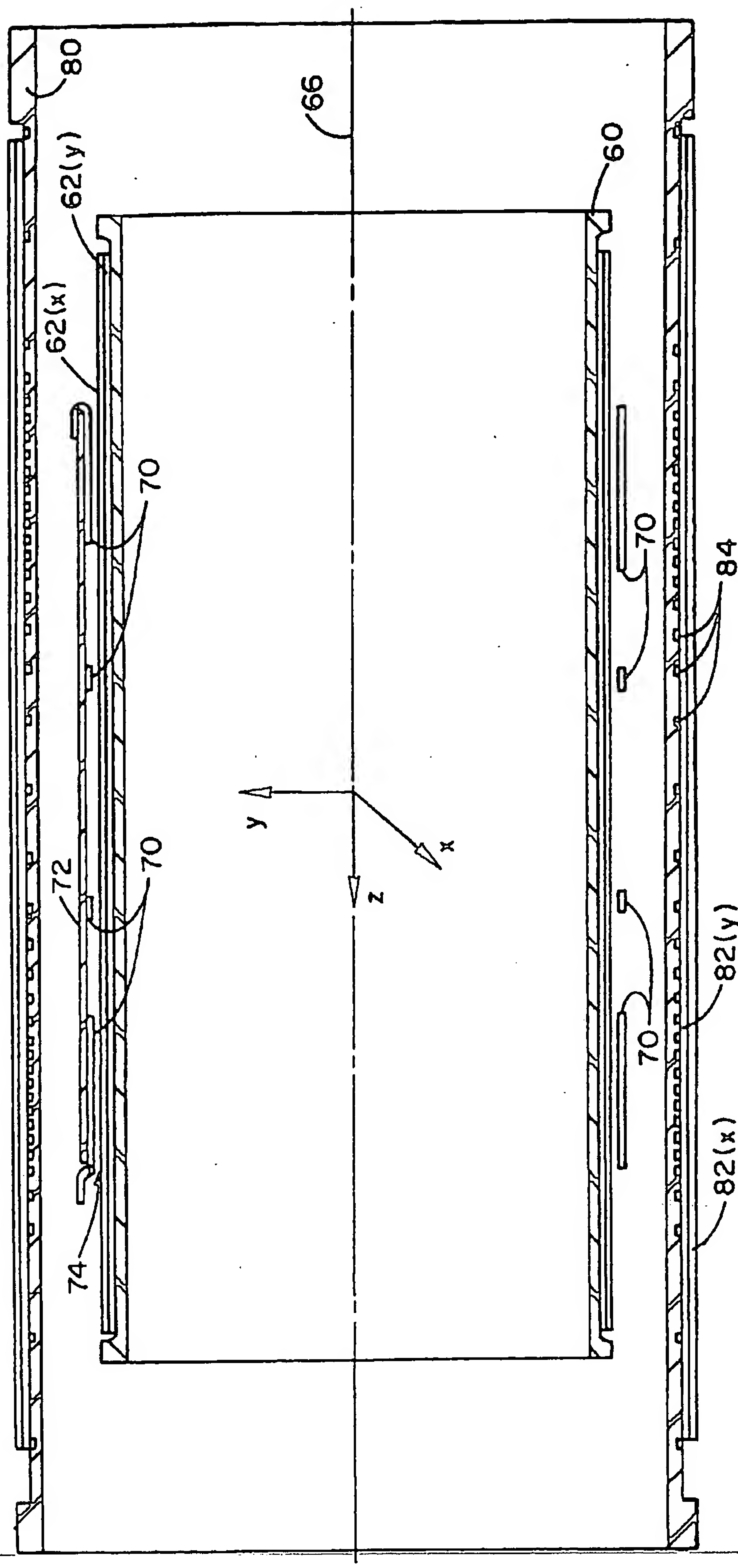

FIG. 2

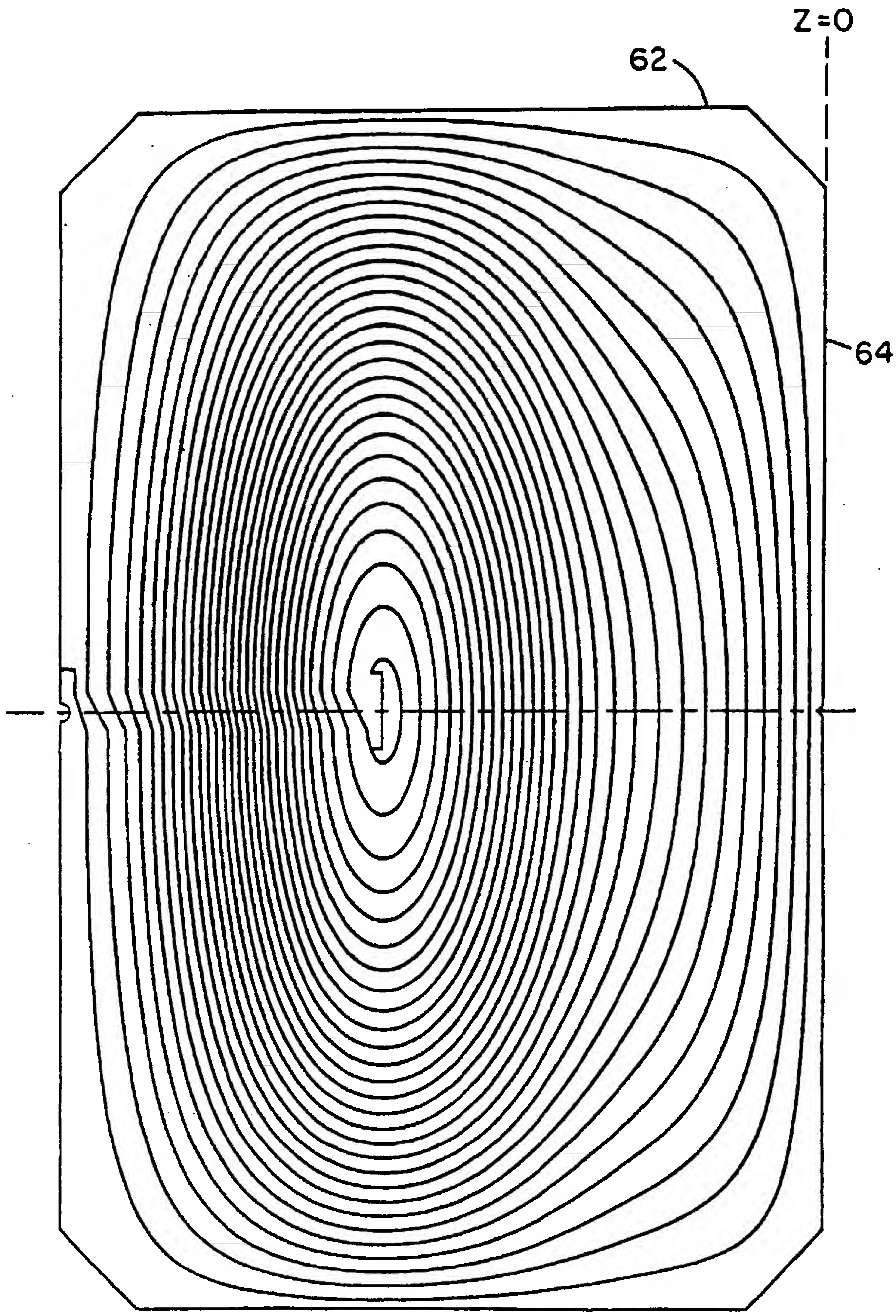

FIG. 3

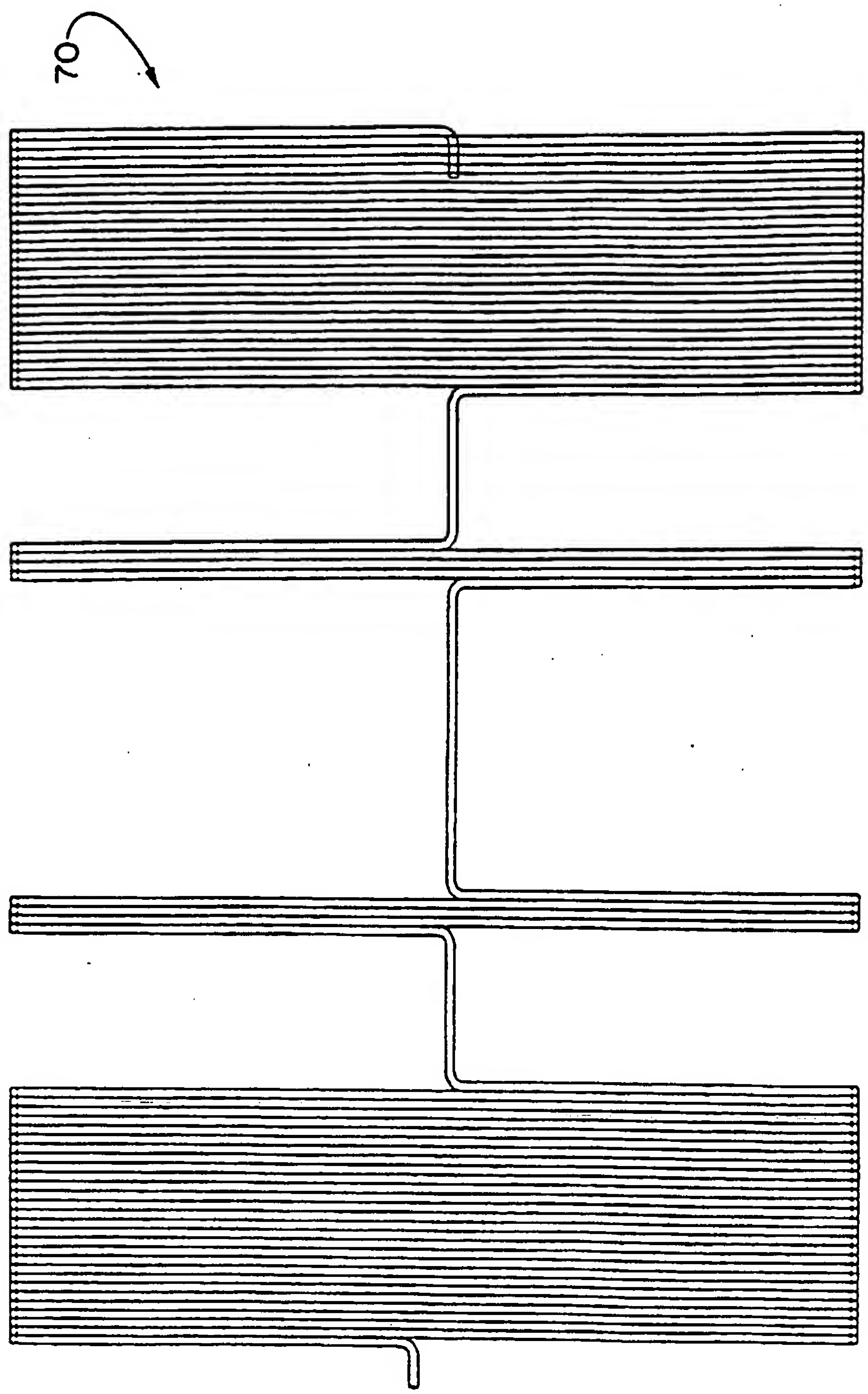

FIG. 4

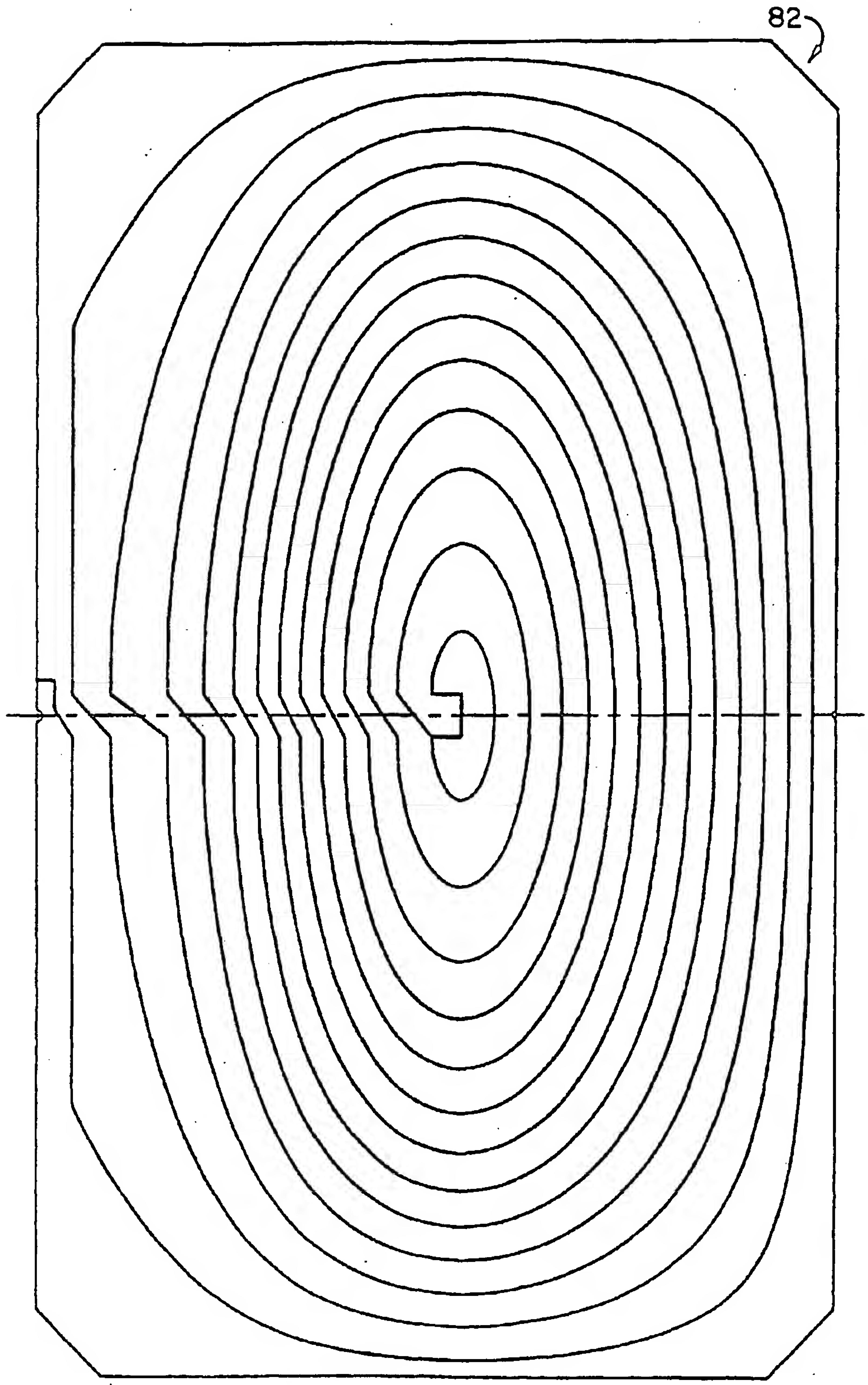

FIG. 5

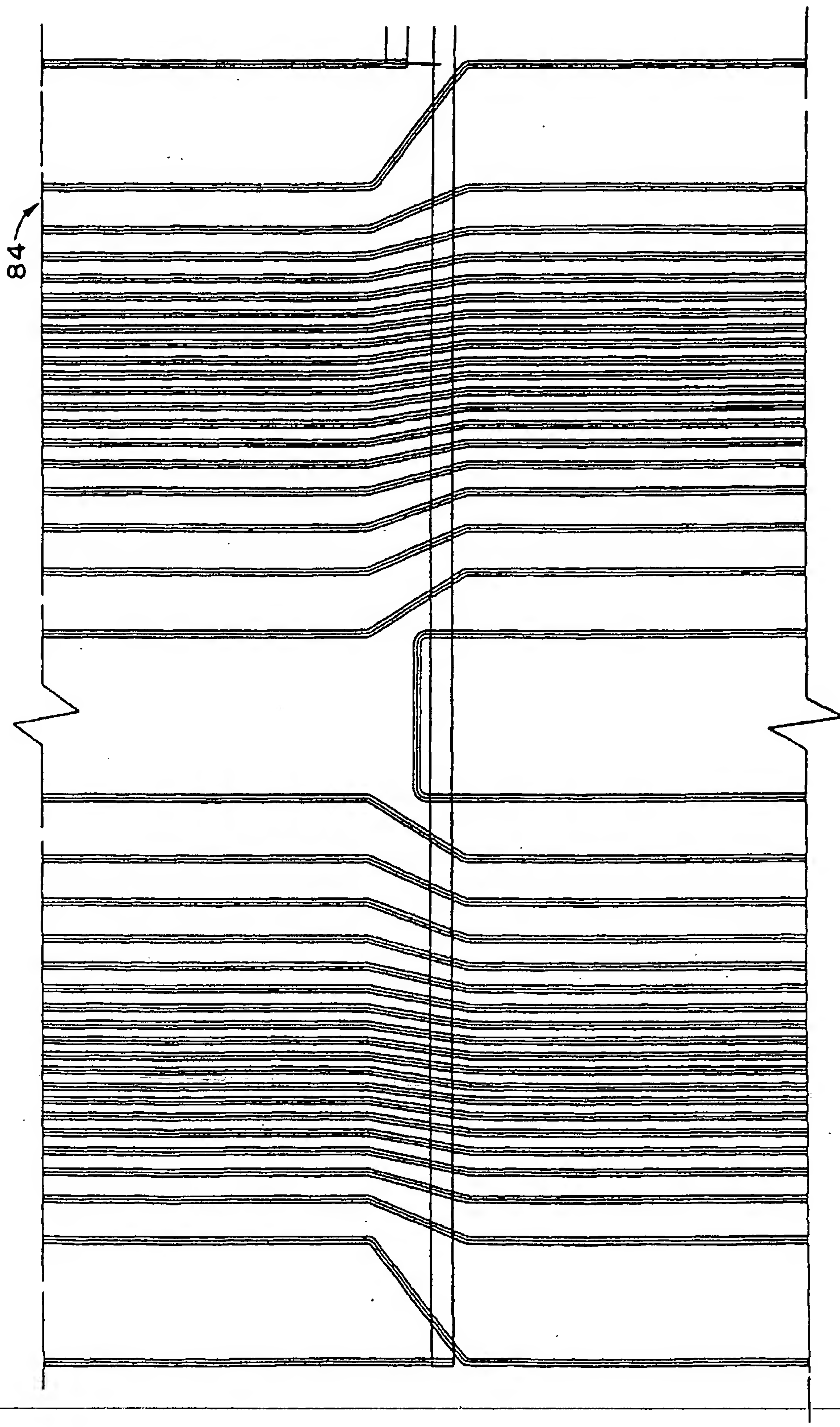

FIG. 6

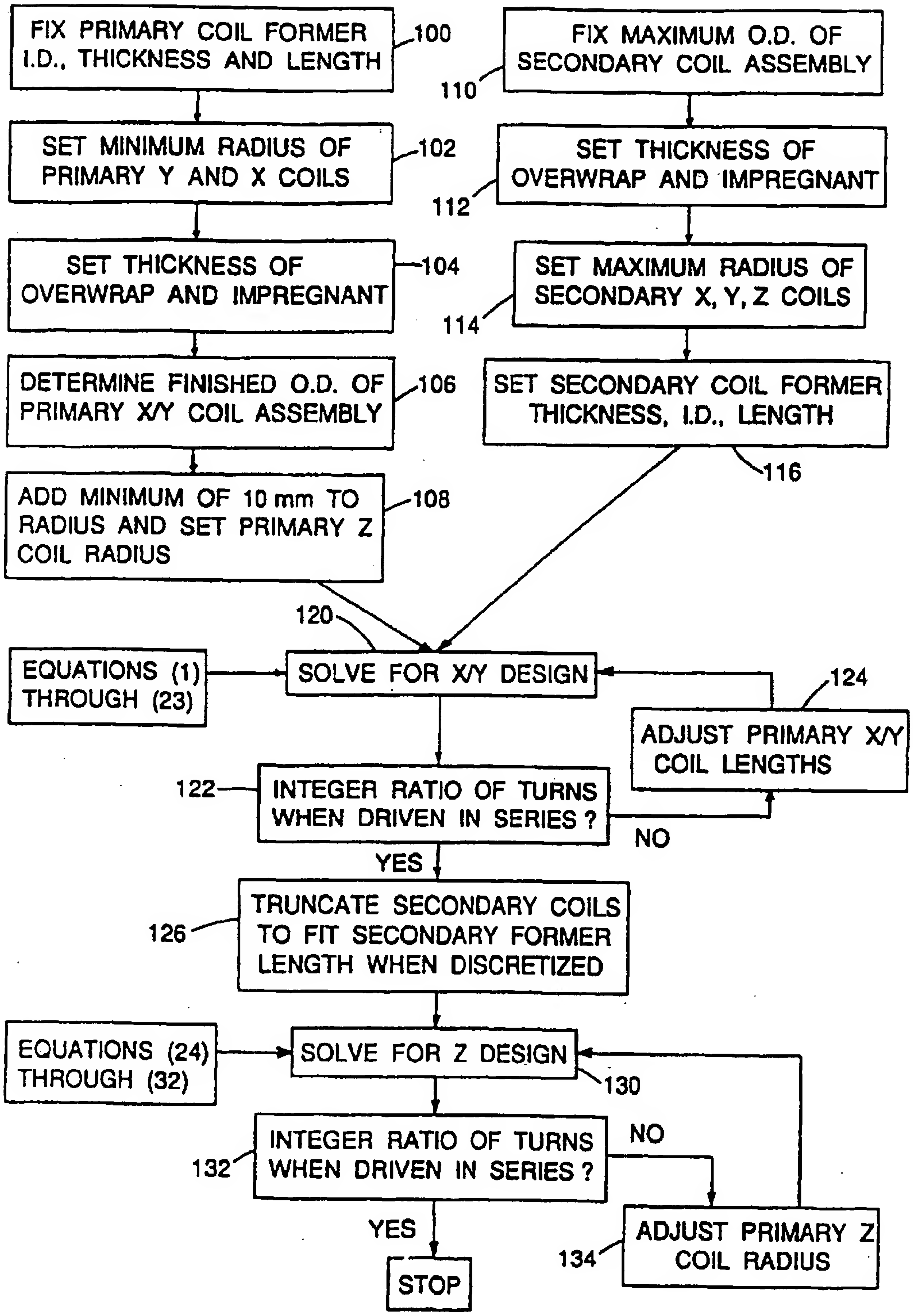
FIX PRIMARY COIL FORMER I.D., THICKNESS AND LENGTH
100
FIX MAXIMUM O.D. OF SECONDARY COIL ASSEMBLY
110
SET MINIMUM RADIUS OF PRIMARY Y AND X COILS
102
SET THICKNESS OF OVERWRAP AND IMPREGNANT
112
SET THICKNESS OF OVERWRAP AND IMPREGNANT
104
SET MAXIMUM RADIUS OF SECONDARY X, Y, Z COILS
114
DETERMINE FINISHED O.D. OF PRIMARY X/Y COIL ASSEMBLY
106
SET SECONDARY COIL FORMER THICKNESS, I.D., LENGTH
116
ADD MINIMUM OF 10 mm TO RADIUS AND SET PRIMARY Z COIL RADIUS
108
120
EQUATIONS (1) THROUGH (23)
SOLVE FOR X/Y DESIGN
124
ADJUST PRIMARY X/Y COIL LENGTHS
122
INTEGER RATIO OF TURNS WHEN DRIVEN IN SERIES ?
NO
YES
126
TRUNCATE SECONDARY COILS TO FIT SECONDARY FORMER LENGTH WHEN DISCRETIZED
EQUATIONS (24) THROUGH (32)
SOLVE FOR Z DESIGN
130
132
INTEGER RATIO OF TURNS WHEN DRIVEN IN SERIES ?
NO
YES
STOP
134
ADJUST PRIMARY Z COIL RADIUS

FIG. 7